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APPLICATION OF COMPONENT SCORING TO A COMPLICATED COGNITIVE DOMAIN

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The recent development of cognitive psychology and science suggests that the lack of understanding of important structural relations between the entities in a problem-solving domain causes difficulties in learning. This study proposes a new scoring method by which the structural relations as well as processes used in subcomponents of the knowledge structure are taken into account when determining the scores. By so doing, a score of "1" derived by wrong reasons will be eliminated and patterns of zeros and ones will contain information closely associated with student's cognitive processes. The procedure is illustrated with basic electricity problems. Keywords:

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Some of the analyses performed in this report were done on the PLATO[R] system. The PLATO[R] system is a development of the University of Illinois, and PLATO[R] is a service mark of Control Data Corporation.

Tatsuoka (1983) showed in the context of signed-number problems that dividing the unit of scores into subcomponents, sign and number parts, enabled us to observe misconceptions possessed by students explicity. However, the recent development of computer technology has made it easier to write computer programs that are capable of solving problems in procedural domains. This study utilizes such work to show cognitive errors occurring at unobservable subcomponents of problem-solving activities.

Riley and her associates (Riley, 1983; Riley, Bee & Mokwa, 1981) have developed a model that represents the theoretical analysis of the knowledge required for successful performance on the Navy's basic electricity and electronics (BE&E) training program. The analysis is presented in the form of a computer program, in other words, a production system which is comprised of two components of knowledge. The first component is a database that includes a network of elements and relations between those elements. The second is a set of production rules which consist of conditions and actions related with "if" and "then" statements. A schematic representation of solving problems in D-C circuits is presented in one of Riley's studies (Riley, 1983). The processes, components of the problem and their relations are expressed in a coherent structure in her paper. Further, an empirical study through a series of interviews with students at the Navy BE&E school revealed that the lack of understanding and acquisition of important components of knowledge structure yielded several errors which were also identified by the theoretical analysis. Montague and Riley constructed a new test by taking these findings into account. This study uses the Montague-Riley test to introduce a new scoring procedure that enables us to see errors in cognitive processes occurring at subcomponents of solving an electricity problem. The scores from the new

scoring procedure reflect the weaknesses and strengths of a student's understanding in the important knowledge components.

Montague-Riley test and a computer program that solves a circuit problem

The tests consist of four parts. Each part includes 36 problems. The content of the test is divided into: 1) series circuits; 2) parallel circuits; 3) and 4) combination circuits. In this study, parts 1) and 2) (simple circuits) are subjected to investigation. As can be seen in Figure 1, the problems are open-ended and require several

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Insert Figure 1 about here

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steps to reach the right answers. These steps are: 1) knowing the terminology and its meanings; 2) understanding the schematic expression of a circuit; 3) setting the known conditions properly that are given in the problem; 4) select an unknown variable that can be solved from the known condition; 5) select appropriate rule(s) expressing various relations among resistors, current and voltage; 6) substitute proper numerals or relations (increase or decrease) in the variables ; 7) solve the equation for the unknown variable; or make a quantitative inference; 8) get the answer; 9) update a set of known conditions.

Independently from Riley's production system, a new computer program was designed and written on the PLATO® system at the University of Illinois (ELTEST, Tatsuoka & Baillie, 1984). Riley's production system uses a backward-search strategy to locate the requested unknown variables which are solvable by the known conditions, but the ELTEST program applies a decision-table strategy which consists of a contingency table of four rows and n columns (the number of resistors plus two columns). The first

	1	2	3	tot	
R	0	+	0		3
E				0	1
I					0
	1	1	1	1	

No. 1

	1	2	3	tot	
R	0	+	0	+	4
E				0	1
I				-	1
	1	1	1	3	

No. 2

	1	2	3	tot	
R	0	+	0	-	4
E				0	1
I	-	-	-	-	4
	2	2	2	3	

No. 3

	1	2	3	tot	
R	0	+	0	-	4
E	-			0	1
I	-	-	-	-	4
	3	2	2	3	

No. 4

	1	2	3	tot	
R	0	+	0	-	4
E	-		-	0	3
I	-	-	-	-	4
	3	2	3	3	

No. 5

	1	2	3	tot	
R	0	+	0	-	4
E	-	+	-	0	4
I	-	-	-	-	4
	3	3	3	3	

No. 6

Figure 1: The condition table of a series circuit problem at six different stages of problem-solving activities

row represents resistors R_i, the second for voltage drop E_i at R_i and the third row for the current at R_i, $i=1,2,\ldots,n$. The fourth row contains the number of total cells filled in the known quantities or the known relations: increase, decrease or unchanged. The n-th column represents the total resistance, total voltage drop, and the total current. The last column includes the number of cells filled in the known quantities or relations. The information in these last rows and columns enables the computer program to solve a problem forwardly instead of backwardly as in Riley's production system. The forwarding path, the ordered string of consecutively solvable variables is uniquely determined except for that E_i and E_j $(i \neq j)$ may be alternated. Riley's theoretical findings that the lack of understanding in the part-whole relations properly causes errors in the answers was taken into acount in the design of ELTEST. The part-whole relationships are decomposed into two parts; that of between columns and within columns (Ohm's law).

The between-column relations include:

$$\sum_{i=1}^{n} R_i = R_t, \ \sum_{i=1}^{n} E_i = E_t, \ I_1 = I_2 = \ldots = I_t \text{ for series circuit,}$$

$$\sum_{i=1}^{n} 1/R_i = 1/R_t, \ E_1 = E_2 = \ldots = E_t, \ \sum_{i=1}^{n} I_i = I_t \text{ for parallel circuits,}$$

and the within-column relations common to both the series and parallel circuits (Ohm's law) are given by,

$$I_i = E_i/R_i, \ i=1,2,\ldots,n.$$

Misconceptions or lack of knowledge

Many errors can be anticipated at any step from 1 to 8 described earlier by a content analysis. However, Riley (1984) found five sources of misconceptions through her protocol study. She reported the frequencies of these errors with a sample of 7 Naval trainees. These errors are described in Table 1 with the same code she used in the previous study.

Insert Table 1 about here

The Montague-Riley test was administered to 250 high school students. Frequencies of their responses to the test items and frequencies of their response patterns as a whole were calculated, and the high-frequency responses are summarized in Table 2.

Insert Table 2 about here

As can be seen in Table 2, quite a few students produced erroneous response patterns different from those of the right responses. The purpose of the next section is to identify the underlying misconceptions which resulted from producing those answers. First, a new scoring procedure (component scoring procedure) that is designed to reflect closely the results of theoretical analysis mentioned earlier into the scores of nine responses will be introduced.

Component scoring procedure

Tatsuoka (1983), Tatsuoka and Tatsuoka (1981) proposed a component scoring procedure in signed-number subtraction problems (number and sign

parts of reponses are scored separately), and formulated a rule space where each erroneous rule of operation was presented as an ordered pair of latent variables θ_1 and θ_2, representing the abilities of calculating the correct

Table 1

Riley's Five Categories of Errors

1.	GC-1	Failure to distinguish the identities of the quantities mapped into circuit formulas.
2.	E = R	Failure to distinguish between voltage drops and resistance.
3.	LG	Mixing local and global variables when Ohm's law was solved.
4.	NA	No Answer
5.	Other	

Table 2

Frequencies of response patterns observed in the problems of series circuits (N = 253)

Problem 1

Frequencies	Response Pattern
132*	+-+-0----
5	+0+0+----
20	+0+0+0000
8	+-+-00000
6	+0000----
5	+-+-+0000
6	+-0-0----
5	+---0----

Problem 2

Frequencies	Response Pattern
108*	-+-+0++++
5	-+-+00000
14	-0-0-0000
34	-+-+0+-++

Problem 3

Frequencies	Response Pattern
28*	+-+-0----
42	+----0-00
32	---------
17	+---0----
10	----0----
9	+0000----
18	0--------
6	00000----
12	0---0----

Problem 4

Frequencies	Response Pattern
159*	+---0----
18	+000+0000
9	+000+----
7	+---00000
5	+---+----
5	+---0000-
6	+--------

*The response patterns listed at the top represent the correct answer.

numbers and signs, respectively, for the answers. However, the problems in the Montague-Riley test are far more complicated than signed-number arithmetic and thus require the help of a computer. For example, Problem 1 in the series circuit test asks:

> What would be the effect of an increase in resistance of R2 on the circuit values?

The students are expected to fill in the boxes displayed in the problem with "+" for increase, "-" for decrease, and "o" for remain fixed. The right procedure starts with filling cell R_2 with "+" and Ea with "0" because the battery voltage (Ea) should always be invariant. Then the cells R1 and R2 must be filled with "0". Figure 2 shows a summary of the successive conditions determined by various stages of problem solving. The only solvable equation in No. 1 of Figure 2 is the relation of the first row: $R_1 + R_2 + R_3 = [\ ]$ and the answer is "+". Then the next step is to

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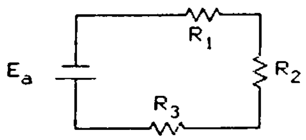
Insert Figure 2 about here

---

apply Ohm's law at the total level in No. 2: $I_t = E_a/R_t$ and the right answer is "-". The next step also follows uniquely: use the relation $I_1 = I_2 = I_3 = I_t$ (because the current is invariant) to fill the cells I_1, I_2 and I_3. Now in No. 3 of Figure 1, apply Ohm's law, $E_1 = I_1 \times R_1$ and $E_3 = I_3 \times R_3$. Then the answers in cells E_1 and E_3 are uniquely determined and they are "-". Since Ohm's law at E_2, $E_2 = I_2 \times R_2$ cannot provide the unique answer with the conditions $R_2 = +$ and $I_2 = -$, the relationship $E_T =$



Mark the appropriate box.

If the resistance of R_2 increases, what happens to:

	Increases	Decreases	No change
R_T			
E_{R1}			
E_{R2}			
E_{R3}			
E_T			
I_{R1}			
I_{R2}			
I_{R3}			
I_T			

Figure 2: A series circuit with three resistors and answer format

$E_1 + E_2 + E_3$ must be used. Since E_T is invariant, E_1 and E_3 are decreasing, the part-whole relation determines E_2 to be +. Thus, the response sequence to the problem is "+ - + - 0 - - - -" when the right procedure is applied. The procedure used in solving each unknown is summarized in the Table 3.

Insert Table 3 about here

The computer program ELTEST, described in an earlier section, was used to score 250 students' responses to the items. The program generates the right answer consecutively for an unknown variable encountered and solves it at each step by using the conditions determined by the previous steps. If the generated response to the question does not match a student's answer, then the program prints the location of the component as well as the conditions used at the current step, picks up the student's wrong response and makes it one of the conditions in solving the next unknown variable (question). The sequential path of solving each unknown variable can be examined by using Table 4. A row of the table represents the

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Insert Table 4 about here

---

necessary conditions to be known in order to obtain the value of a column variable with one type of four arithmetic operations without any combination. For example, $E_1 = E_4 = -E_2 - E_3$ is a simple operation but $E_2 = (E+/R+) \cdot R_2$ is a combination. The variation of paths of solving unknown variables are only within a step, hence in terms of scoring applications of rules the path difference is trivial and does not affect component scoring

Table 3

Summary of the right procedure at each step of solving the unknowns

Variable	Current Condition	Relation to be used	Answer	Order of steps
R_t	$R_1=0$, $R_2=+$, $R_3=0$, $(E_t\equiv 0)$	$R_t=R_1+R_2+R_3$	+	2
E_1	$R_1=0$, $I_1=-$	$E_1=I_1 \times R_1$	-	7
E_2	$R_2=+, I_2=-$	$E_2=I_2 \times R_2$	**	8
	$E_1=-$, $E_3=-$, $E_t=0$	$E_t=E_1+E_2+E_3$	+	10
E_3	$R_3=0$, $I_3=-$	$E_3=I_3 \times R_3$	-	9
E_t	$E_t\equiv 0$	Terminology	0	1
I_1	$I_t=0$	$I_t=I_1$	-	4
I_2	$I_t=0$, $I_1=0$	$I_t=I_1=I_2$	-	5
I_3	$I_t=0, I_1=0, I_2=0$	$I_t=I_1=I_2=I_3$	-	6
I_t	$E_t=+$, $R_t=+$	$I_t=E_t/R_t$	-	3

**Impossible to diagnose

Table 4

Prerequisite conditions to derive the correct values of the column variable

	R+	E_1	E_2	E_3	E_t	I_1	I_2	I_3	I_t	
R+					1				1	step 2
E_1			1	1	1	1				
E_2		1		1	1		1			step 5
E_3		1	1		1			1		
E_t	1	1	1	1					1	step 3
I_1		*	*	*	*	*	*	*	*	
I_2		*	*	*	*	*	*	*	*	step 4
I_3		*	*	*	*	*	*	*	*	
I_t	1	*	*	*	*	*	*	*	*	
R_1	1	1				1				
R_2	1		1				1			step 1
R_3	1			1				1		

* Within each column one of the *'s needs to be known

1 To solve unkown column variable necessarily being know row variables are coded as 1

2 This coding is based on a serial circuit with 3 resistors

at all.

The scoring at a particular point is based on the correctness of applying the appropriate rule using preceding conditions, hence, the worng response at a particular point does not effect the score of later variables. This scoring enables us to identify the exact spot where an erroneous application of a rule was made. For example, the following student produced the response pattern shown in Table 5.

Insert Table 5 about here

The example given in Table 5 can be diagnosed as follows:

1) The student lacks the knowledge that Ea = remains fixed;

2) at $E_1 = I_1 \times R_1$, substituting "unchanged" and "decrease" in R_1 and I_1, respectively, E_1 should be decreased. The same action is repeated at E_3;

3) at $I_t = E_t/R_t$, the answer should be undetermined, but the response is -. The student's error is due to a lack of understanding of the algebraic relationships of Ohm's law.

Discussion

This study displayed the successful application of the component scoring method in the domain of electronics, which is more complicated then the signed-number subtraction domain. This scoring method is applicable and useful unless the number of components is unmanageably large.

The immediate return of component scoring is being able to identify where the error was made. This leads directly to a remediation scheme for a particular error. The evaluation of component scores is difficult to do. One way to do this evaluation is to ask how objective the scoring is by examining sources of variations of scoring and the meaningfulness of these

Table 5

Comparison between component scoring and traditional "right or wrong" scoring procedures

Problem	Answer	Component Scoring	Traditional Scoring	Right Answer
R+	+	1	1	+
E_1	0	0	0	-
E_2	+	1	1	+
E_3	0	0	0	-
E_a	+	0	0	0
I_1	-	1	1	-
I_2	-	1	1	-
I_3	-	1	1	-
I_T	-	0	1	-

variations. Using some information similar to the table, one can answer these two questions. In this study there was only one general sequential path, and the variation within the general path produced identical results, hence variation was trivial.

The other way to evaluate the scoring is to compare the item by item correlation matrix of component scoring and regular scoring. If the scores reflect the knowledge of electricity circuits, then the correlations of scores should be non-negative. It was found that there were eleven significantly large negative correlations for the regular scoring, while only one in the component scoring.

The number of components can be derived by first making a theoretical study of materials to be tested and further modified after the pilot study, and then validating the components by comparing the real data and the responses simulated by the erroneous rules of various components. Benefits of component scoring are far reaching. For example, instead of a very specific conditional description needed to express the erroneous rule in one component (right or wrong responses), the component scoring method can express most of the erroneous rules by the combination of components and component specific errors. For example if three errors are identified with each of four components then 3**4=81 combinations of possible erroneous rules exist; and each of 81 erroneous rules can be specifically defined by only 12 rules. Other benefits of the component scoring method are realized when responses are mapped on to the rule space (Tatsuoka, 1984) by using right or wrong response patterns. Some rules can have small spatial distances on the rule space but the response patterns are distinctly unique. For such a case, if the component scoring method were utilized, two response patterns can be distinguished more precisely.

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